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Design of very-high-flow coefficient centrifugal compressor stages

Centrifugal compressors are widely used in the oil and gas and petrochemical industries, with more than 15,000 operating in the U.S. alone. The abundance of inexpensive shale gas has fueled a growing global demand for hydrocarbon derivatives, such as ethylene and propylene. Operators are taking advantage of these market conditions to increase plant capacity, and compressor manufacturers are being asked to build larger compressors to meet ever-higher volumetric flow requirements.

As compressors get larger, however, they are more expensive to build and maintain, and often require a bigger footprint. One approach to satisfy growing capacity needs without increasing the footprint is to maintain the compressor's frame size, while increasing internal flow capacity. This requires the development of advanced 3D aerodynamic very-high-flow coefficient shrouded impeller stages and associated flow path designs.

To address this need, the author's company initiated a multi-generational design project to develop a lineup of high-flow coefficient compressor stages. During the design process, state-of-the-art computational fluid dynamics (CFD) were used to develop aerodynamic flow path designs validated through prototype testing in a dedicated closed-loop facility. The outcome of this project was the successful development of some of the highest-flow coefficient, state-of-the-art centrifugal compressor stages available in the industry for oil and gas applications. These stages significantly exceed the flow and efficiency capabilities of previous industry impeller designs, while maintaining structural integrity and providing a wide operational range. The project also explored new aerodynamic tools and technologies that will be used in the design of the next generation of very-high-flow coefficient centrifugal compressor stages.

Aerodynamic design. In general, compressor design refers to the selection, sizing and layout of field-proven compressor components, while aerodynamic design refers to the design process for those components. Specifically, aerodynamic design is about sizing and shaping the compressor flow path and blading to guide the fluid and efficiently transfer rotational mechanical energy.

For increased duty and volume flow, centrifugal compressors with higher energy density provide financial incentives. The smaller footprint of the compression equipment has a definite positive impact on initial capital and operational expenses, along with improved operating capabilities. However, this cost reduction is justified only if the compressor delivers robust performance, long life, high efficiency and a wide operating range.

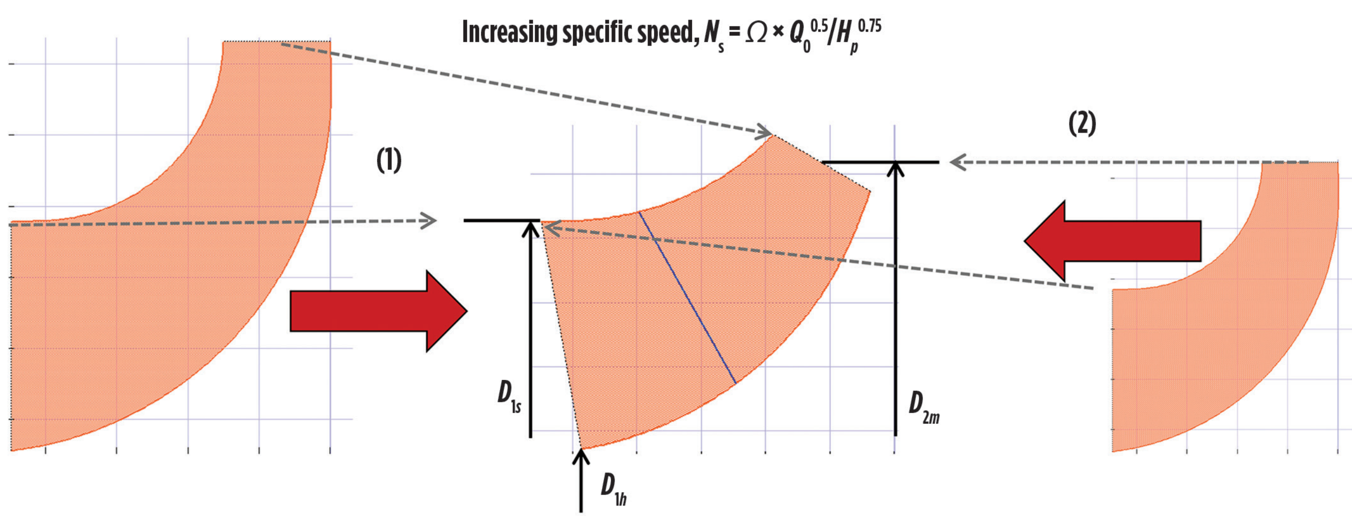

FIG. 1. A path toward high-specific-flow stages. N_S = specific speed; Ω = rotational speed, rpm; Q_0 = suction volume flow; H_P = polytropic head.

FIG. 2. Original design of the very-high-flow impeller (top), with circumferentially averaged meridional distribution (bottom).

Consequently, the compressor design process becomes a complex optimization of several performance attributes and operational requirements.

As compressor stages become more compact, as shown in FIG. 1 (left to center), their swallowing capacity (flow per frontal area) must increase when processing the same original mass flow. This increase is directly proportional to the product of flow coefficient and machine Mach number, which means that either the flow coefficient and/or the Mach number must increase. As the flow coefficient increases, the impeller's specific speed also increases, which can lead to changes in impeller architecture (e.g., going from purely radial to mixed-flow style impellers), as shown in FIG. 1 (right to center).

From a conventional design perspective, it is possible to keep the same frontal area and to increase inlet flow by raising the inlet shroud radius for a purely radial transformation, as shown in FIG. 1 (right to center). However, by increasing the specific speed above 1, the radius ratio across the impeller shroud rapidly tends toward unity, leading to a successively lower contribution of Coriolis forces to head rise. The shroud curvatures also tend to become excessive, leading to higher losses. In addition to achieving flow capacity, the need to produce sufficient head per stage makes this design challenging.

Given these complexities, the author's company conducted a long-term design and testing project to develop the next-generation very-high-flow coefficient impeller stage, exceeding a 0.237 flow coefficient. This stage will serve as a design basis for future derivative stage designs at even higher flow coefficients.

Compressor impeller design. To provide a solid footing for this design development, an evolutionary, multi-generational, iterative approach was used. This comprised a combination of proven engineering practices and advanced novel computational tools to meet the design requirements. To ensure the integrity of the optimization process, the first design iterations did not significantly depart from established practices, and operationally validated proven impeller designs. For example, the original stage design only marginally extended flow capacity beyond the

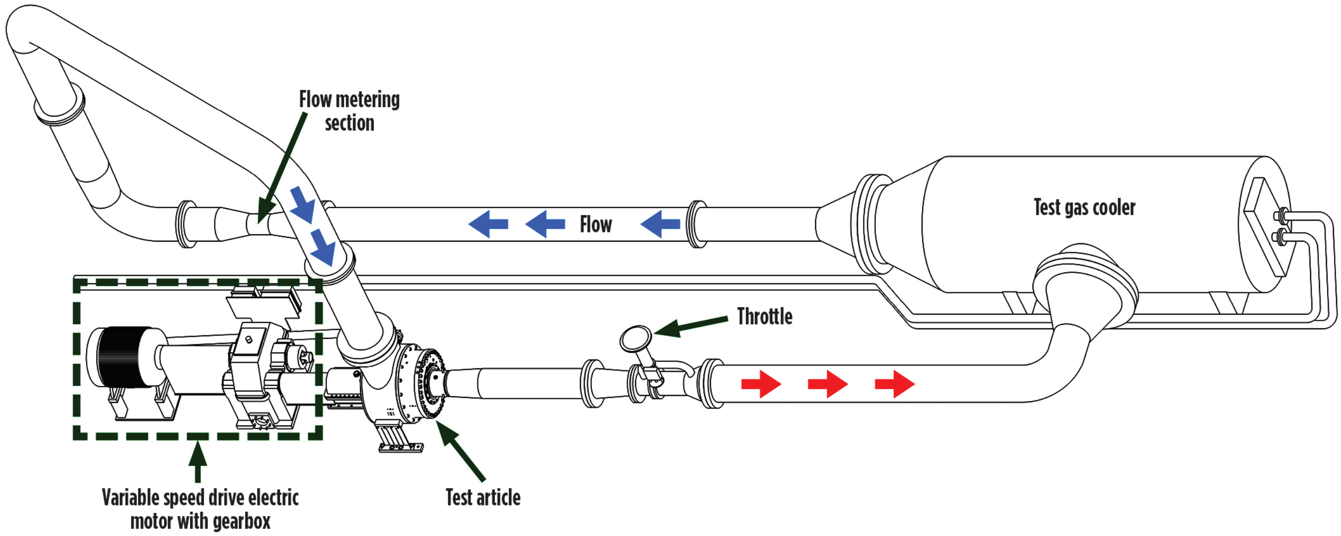

FIG. 3. Closed-loop centrifugal compressor test facility.

existing stage offering for a fixed frame size. Although it featured a higher Mach number and a mixed-flow shrouded impeller with relatively compact stage space, this first exploratory concept was not designed to drastically depart from previous high-flow designs. FIG. 2 (top) shows this first-generation impeller, with its large inlet area and a plurality of industry-standard, 3D, straight-line element blades and two-piece construction. The blade count was kept low to reduce metal blockage and to maximize the geometric throat area. The stationary components downstream of this mixed-flow impeller included a curved vaneless diffuser, crossover and return channel with two-dimensional extruded vanes. FIG. 2 (bottom) illustrates the meridional projection for the entire stage, along with contours of circumferentially mass-averaged meridional velocities at the design point.

Results from testing of the initial design fell very much along the extrapolated trends shown by the existing stage portfolio, thus validating the design and optimization process. While this impeller design had the capability to operate at the proposed flow and produce the necessary head and stall margin, additional aerodynamic optimization was necessary to meet the high efficiency targets and operating range design requirements. Areas that required further design adjustments included component loss reduction, stage-exit swirl control and flow profile uniformity.

Design optimization. For the subsequent iterations, complex aerodynamic and structural design challenges needed to be addressed, while maintaining a high level of confidence in the performance predictions—without affecting impeller integrity.

To improve prediction confidence, critical computational analysis and design tools were validated and anchored in test data at a laboratory-rated scale compressor impeller closed-loop test facility (FIG. 3). The facility is designed to closely address ASME PTC-10 requirements. It uses simulated process gas, and can operate near compressor full-flow, speed and head conditions to obtain high-fidelity dynamic compressor performance data, using a state-of-the-art, high-speed data acquisition system.

Some of the additional modifications included in this second-generation impeller design iteration included a splitter configuration with fully 3D, free-form blades. The splitter configuration significantly opened the geometric throat area to allow higher flow capacity. Necessary diffusion is provided by carefully controlling the distribution of the impeller passage area. Specifically, the splitters were strategically located in meridional and circumferential planes to control loading and secondary flow losses, and were constructed with blade angle distributions for optimal efficiency and a wider operating range.

At the design point, the impeller is still operating at subsonic and reasonable inlet relative Mach numbers. Blade incidence angles and the inducer section surface curvatures were carefully tailored to reduce excessive acceleration and the possibility of terminal shock, and to prevent the breakdown of blade loading at off-design conditions. Similarly, blade loading was optimized to avoid hub-to-shroud secondary flow migration and to reduce aerodynamic blockage.

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FIG. 4 shows the second-generation impeller (top and middle) and meridional projections (bottom). Not only are the overall levels of circumferentially mass-averaged meridional velocities decreased, but also the velocity field is clearly seen to be more uniform. The low momentum fluid near the crossover shroud is also significantly reduced, leading to reduced frictional and mixing losses.

Aerodynamic and structural considerations. Shrouded impellers are usually preferred for multistage centrifugal compressor designs because of their better aerodynamic performance and lower susceptibility for blade interaction dynamics. However, for most conventional higher-specific-speed designs, impellers are generally unshrouded to minimize steady hoop stresses on the blades. Specifically, in shrouded impellers, the added weight of a shroud can increase blade stresses. Additionally, the wider impeller tip can result in considerable centrifugal bending stresses, while tall blades, as is the case here, have lower natural frequencies. While these are structural design challenges that must be considered, a careful finite element stress analysis, coupled with iterations between aerodynamic and dynamic structural design, can be utilized to mitigate the increased stress loading on the blades to maintain a structurally solid impeller design while maintaining optimal aerodynamic performance.

Stationary stage components can contribute significantly to stage inefficiency in the high-flow-coefficient regime, and usually require careful geometric sizing and shaping to limit frictional and secondary flow mixing losses. These losses were minimized,

FIG. 4. View of the very-high-flow, mixed-flow impeller (top and middle) and the circumferentially averaged meridional distribution (bottom).

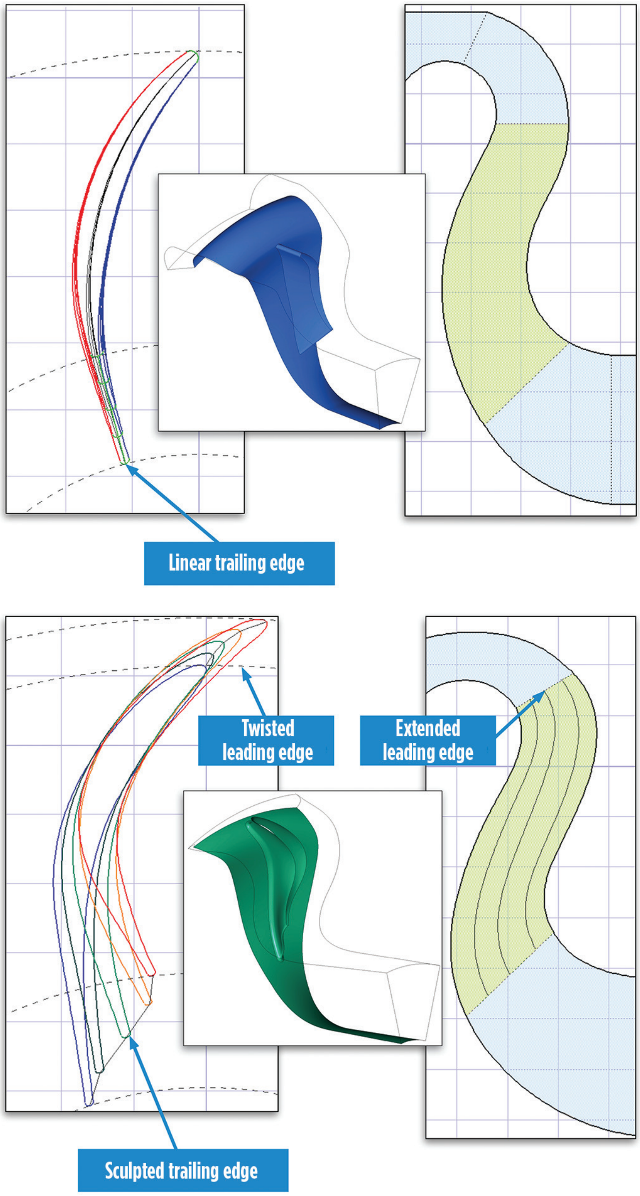

FIG. 5. Return channel vane design iterations. Generation 1 (top) has a 2D return channel, while Generation 2 (bottom) has a 3D return channel vane.

using a customized 3D impeller trailing edge to reduce migration of flow into the shroud suction side corner and to provide a more uniform meridional velocity profile entering the diffuser. It is also generally expected that the flow exiting from the return channel will have not only a low average swirl, but also a reasonably uniform swirl distribution. To control this highly complex flow more precisely, a fully 3D, multi-section return channel vane—with the leading edges extended into crossover, sculpted body and twisted leading edges—was designed (**FIG. 5**). The extended leading edge begins processing the flow sooner than the conventional 2D vane before the velocity profile deteriorates toward the crossover exit.[1,2] The twisted leading edge affords good control over span-wise incidence variation, and the sculpted body provides strong control over competing secondary flows. Overall, this design approach provides excellent distribution of span-wise swirl without incurring additional total pressure losses.

Finally, most high-flow coefficient impellers from the author's company will be manufactured using single-piece construction to improve manufacturing tolerance. This also helps reduce metal blockage and its adverse effect on aerodynamic performance and aeromechanics response.

Improved very-high-flow stage performance. An advanced design, single-piece, very-high-flow impeller and a return channel were tested over multiple speed lines and with different gases in the closed-loop test facility. The measured performance met or exceeded all design targets, demonstrating consistently high efficiency over a wide operating range, along with a robust dynamic performance. This new stage forms the basis of the family of very-high-flow-coefficient stages, which has extended stage portfolio by 33% in flow capacity.

In designing a high-flow-coefficient centrifugal stage, several competing aerodynamic and structural design choices must be considered. Advanced engineering design, analysis and simulation tools were used to develop the next-generation, very-high-flow coefficient centrifugal compressor stage. The resulting design is a solid, reliable and aerodynamically well-balanced compact stage, which delivers wide operability and excellent design point performance. This evolutionary design effort has resulted in centrifugal compressor stages that can allow for higher flows and that can reduce a compressor casing size to better address customer application-specific needs. HP

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